Key Atmospheric Plasma Solutions Lead Reliable Hybrid Bonding

Kelvin Chiu, Kuo-Chao Liang, Chun-Cheng Wu, Winson Hsu
Nano Electronics and Micro System Technologies, Inc.
No. 100, Keji 5th Rd., Tainan Technology Industrial Park, Annan District,
Tainan City 709035, Taiwan
Ph: +886-6-2915500 ; Fax: +886-6-3845808
Email: klchiu@nemstek.com.tw

Abstract
Surface pre-treatment is crucial for achieving high-quality hybrid bonding in advanced semiconductor packaging. This paper presents the development and characterization of a Medium Frequency Atmospheric Pressure Dielectric Barrier Discharge (MF AP-DBD) plasma system designed for this application. Unlike conventional RF or Microwave plasma systems that typically require expensive noble gases like argon, the developed MF AP-DBD source effectively utilizes cost-efficient high-concentration nitrogen as the working gas, combined with a small percentage of hydrogen for reduction. We evaluated the system's performance through experiments focusing on copper oxide reduction effectiveness, treatment uniformity across its 320 mm width, and the influence of key operating parameters. Results demonstrate that the plasma effectively reduces copper oxide. Uniformity tests confirmed satisfactory treatment across the width, with parameter tuning achieving over 80% effective width under optimized conditions (e.g., 600-1000W, 60-100slm N_2 with 1 vol% H_2 at 1mm/s). Furthermore, a ground electrode design successfully maintained substrate electrostatic charge below 10V despite the high operating voltage. These findings highlight the potential of the MF AP-DBD plasma as a cost-effective, uniform, and electrostatically controlled solution for surface pre-treatment in hybrid bonding.

Key words
Atmospheric Pressure Plasma, Medium Frequency, Nitrogen, Copper Oxide Reduction, Uniformity, Electrostatic, Hybrid Bonding.

I. Introduction
Hybrid Bonding technology represents a cutting-edge innovation in modern semiconductor packaging, driving chip manufacturing towards a three-dimensional integration era characterized by higher density, superior performance, and further miniaturization[1]. A core breakthrough of this technology is its capacity to achieve highly precise connections at the wafer or die level. This process involves not only the direct, atomic-level bonding of copper metal surfaces but also the integration of covalent bonding between dielectric materials, thereby forming extremely dense interconnect interfaces.

In the hybrid bonding process, surface cleaning and activation are pivotal steps. Plasma technology, known for its exceptional surface treatment capabilities, has become an indispensable enabler for achieving high-quality hybrid bonding. Plasma, often referred to as the fourth state of matter, is a partially ionized gas containing a rich variety of active species, including ions, electrons, free radicals, and excited-state atoms and molecules. These active particles interact effectively with material surfaces to achieve efficient and multifunctional surface treatment effects. Plasma technology offers several key advantages in the pre-treatment phase of hybrid bonding: It provides efficient surface cleaning by removing organic contaminants through chemical reactions and effectively removes native oxide layers in a reducing plasma environment. Plasma also enables effective surface activation, increasing surface hydroxyl groups on dielectric materials, which enhances hydrophilicity and surface energy crucial for tight surface contact and subsequent high-strength covalent bonding. Furthermore, plasma treatment is a low-temperature process, which reduces thermal stress and budget and is applicable to heat-sensitive materials. It is also a dry process, reducing chemical usage and avoiding re-contamination issues associated with wet cleaning methods.

Addressing the stringent pre-treatment requirements of hybrid bonding, our group has developed a suite of atmospheric pressure plasma source technologies. While we have previously developed Microwave and RF plasma systems for similar applications, both of these designs typically require expensive argon inert gas as the primary working gas, with the addition of only a small concentration (< 1 vol%) of hydrogen for reducing surface copper oxide. Motivated by the need for more cost-effective and flexible processing, we have therefore dedicated efforts to the development of Medium Frequency Atmospheric Pressure Dielectric Barrier Discharge (MF AP-DBD) Plasma technology. This particular type of plasma is distinguished by its operational flexibility and economic advantages. Crucially, the MF AP-DBD plasma technology is capable of effectively utilizing high-concentration nitrogen gas (N_2) as the primary working gas. This is a significant advantage as nitrogen is considerably less expensive than noble gases like helium or argon often required by other plasma sources, leading to substantial reductions in operational costs. DBD plasma sources are also known for generating relatively uniform plasmas at atmospheric pressure and can accommodate various reactive gas chemistries, providing flexibility to tailor the surface treatment for different material sets and bonding requirements.

Furthermore, a significant overarching benefit of atmospheric pressure plasma technologies, including the MF AP-DBD system, lies in their inherent suitability for seamless integration into in-line automated production lines, unlike vacuum-based systems. Operating at atmospheric pressure also mitigates potential damage mechanisms often associated with high-energy vacuum plasmas. This paper will therefore concentrate on the investigation of the MF AP-DBD plasma system and its application in surface pre-treatment for hybrid bonding, particularly leveraging its ability to operate efficiently and cost-effectively with high-concentration nitrogen gas.

II. Experiments

The experimental system used in this study is illustrated in the schematic diagram shown in Figure 1. The core component is a plasma unit measuring 410 mm (length) × 70 mm (width) × 75 mm (height). This unit is designed to generate a line-shaped plasma with an effective width of 320 mm. The plasma operation power was typically set within the range of 800 to 1000 W, driven by a 60 kHz power supply.

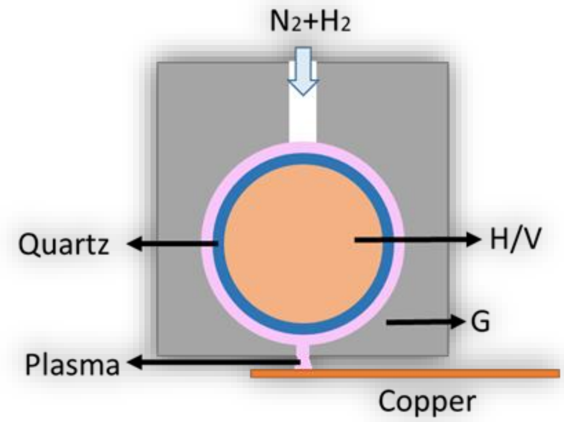

Figure 1: Schematic diagram of the experimental plasma system, illustrating the reaction chamber, gas inlet, and substrate configuration with labeled components: H/V (powered electrode), G (ground electrode), and quartz (dielectric barrier).

The experimental conditions employed were as follows: The gap between the electrode and the substrate was maintained at 1.5 to 2 mm. A plasma scanning speed ranging from 1 to 5 mm/s was used. The reactive gas mixture consisted of 40 to 100 slm of a gas flow containing 1.0 vol% H_2 balanced with N_2. The total gas flow rate was controlled within the range of 40 to 100 slm. Throughout the experiments, the substrate holder temperature was kept at 160 to 180 ℃.
The experiments in this study were primarily conducted in the following directions:

- Copper Oxide Reduction Effect: Investigating the efficiency and extent of copper oxide reduction by plasma treatment.
- Reduction Uniformity: Analyzing the uniformity of the reduction reaction across the material surface or target area after plasma treatment.
- Plasma-Induced Electrostatic Strength Measurement: Experimentally quantifying the electrostatic field strength generated during plasma processing.

The experimental results for each of these directions will be analyzed and discussed in detail in the following sections.

III. Results and Discussion

Firstly, we tested the reduction capability of the MF plasma on a copper oxide film. The specific test conditions employed for this evaluation were as follows: Plasma power was maintained between 800 and 1000 W. The gas flow consisted of 80 slm N_2 and 1.0 vol% H_2. The gap between the plasma source and the substrate was 2 mm, and the scanning speed was 1 mm/s. The substrate heating temperature was kept at 160–180 ℃, and the test was conducted under atmospheric pressure. To facilitate the judgment of the treatment effectiveness, we affixed PI tape onto a copper piece to mask a portion of the surface area. After the MF plasma treatment, the PI tape was removed, and the color change of the copper piece was inspected (as shown in Figure 2). It was observed that the plasma-treated copper surface, which initially had a reddish film characteristic of CuOx, transformed into the color of metallic copper. This color change indicates that the MF plasma effectively reduced the copper oxide to metallic copper.

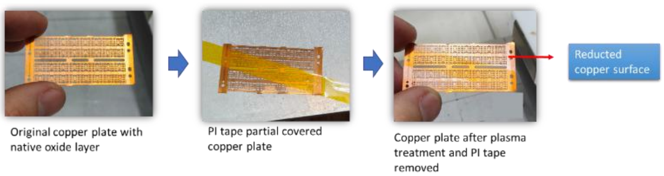

Figure 2: Visual evidence of copper oxide reduction on a copper plate treated with MF AP-DBD plasma. (left) Original copper plate with native oxide. (middle) Plate with partial PI tape coverage. (right) Plate after plasma treatment and tape removal, clearly showing the reduced metallic copper surface compared to the untreated area.

Secondly, we evaluated the uniformity of the copper reduction across the 320 mm width of the MF plasma. The test conditions were set as follows: Power at 800 W, gas flow of 80 slm N_2 and 1.0 vol% H_2, a gap of 2 mm, a scanning speed of 1 mm/s, substrate temperature between 160–180 ℃, and conducted at atmospheric pressure. As shown in Figure 3, we divided the copper piece into four areas along the width of the plasma and compared the surface color after reduction. No significant difference in surface color was observed among these areas. Therefore, it was initially determined that the treatment capability across the entire 320 mm width of the plasma was not significantly different, indicating good uniformity.

Furthermore, we investigated the influence of different operating parameters on the entire 320 mm treatment width. As presented in Table 1, parameters such as gas flow rate, plasma power, and scanning speed were found to affect the effective treatment width. It was observed that the treatment effectiveness in the central region of the plasma was superior to that in the edge regions. Specifically, when the scanning speed was maintained at 1 mm/s, sufficient reduction effectiveness, defined as achieving the desired surface transformation across more than 80% of the width, could be obtained with N_2 flow rates ranging from 60 to 100 slm and plasma power from 600 to 1000 W.

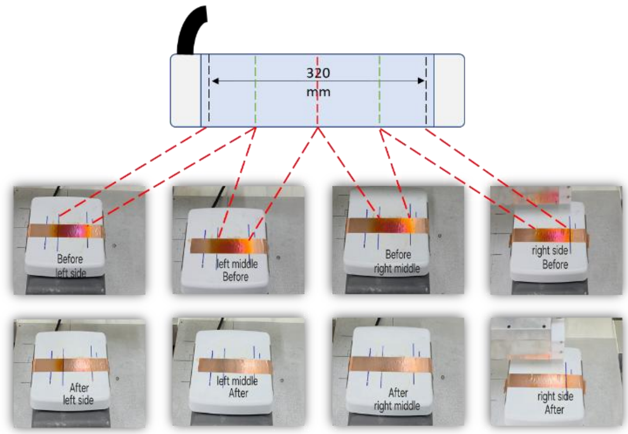

Figure 3: Evaluation of plasma treatment uniformity. Images show copper plate sections from four different positions along the 320 mm plasma width, before and after treatment, demonstrating uniform reduction.

Table 1: Lateral uniformity of copper surface with plasma parameter variation

Speed (mm/s)	N_2 with 1% H_2 (slm)	Power(W)		
		600	800	1000
1	40	■	■	●
	60	●	●	●
	80	●	●	●
	100	●	●	●
3	40	╳	■	■
	60	●	●	●
	80	■	●	●
	100	▲	▲	●
5	40	╳	╳	■
	60	■	■	■
	80	■	▲	▲
	100	╳	■	■
10	40	╳	╳	╳
	60	╳	╳	╳
	80	╳	╳	╳

	100	╳	╳	╳

●: > 80% reduction area
▲: 60~80% reduction area
■: 40~60% reduction area
╳: < 40% reduction area

Finally, we investigated whether the electrostatic charge induced by the MF AP-DBD plasma would be excessively high. Since the DBD-type MF plasma utilizes a high-voltage power supply (>5 kV), a ground electrode slit was implemented at the plasma exit (as illustrated in Figure 1) to mitigate potential electrostatic issues induced on the substrate by the high voltage. The architecture of the system used for this test is shown in Figure 4. A Keyence SK-H050 electrostatic voltmeter was used to measure the static charge on the substrate surface under the following test conditions:

- Power: 1000 W
- Gas flow: 80 slm (Note: Specify gas composition if it differs from N_2 + 1% H_2)
- Gap: 2 mm
- Scanning speed: 1 mm/s

The measured electrostatic value on the substrate surface remained below 10 V. This result indicates that the design incorporating the ground electrode effectively isolates the high electric field and prevents excessive charge accumulation on the substrate.

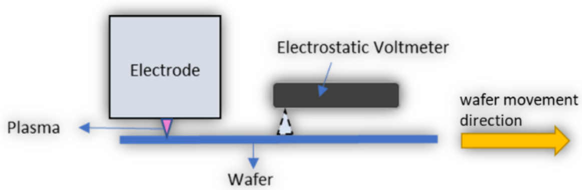

Figure 4: Schematic diagram of the experimental setup for measuring substrate electrostatic charge

IV. Conclusion

In this study, we investigated the characteristics and performance of the Medium Frequency Atmospheric Pressure Dielectric Barrier Discharge (MF AP-DBD) plasma system for surface pre-treatment. Our evaluation of copper oxide reduction effectiveness demonstrated that the MF AP-DBD plasma, utilizing an N_2 and H_2 gas mixture, is capable of effectively reducing native copper oxide films to metallic copper, as evidenced by the clear color transformation observed. Furthermore, initial uniformity tests confirmed that the 320 mm wide plasma discharge provides a relatively uniform treatment across the width. A detailed study on the influence of operating parameters revealed that gas flow rate, plasma power, and scanning speed significantly impact the effective treatment width, with better uniformity observed in the central region. Optimized conditions, specifically N_2 flow rates of 60–100 slm and plasma power of 600–1000 W at a scanning speed of 1 mm/s, were found to yield sufficient reduction effectiveness across more than 80% of the treatment width. Finally, despite operating with a high-voltage power supply, the system incorporating a ground electrode slit effectively mitigated electrostatic charge build-up on the substrate surface, maintaining charge levels below 10 V. These results collectively indicate that the developed MF AP-DBD plasma system offers effective, relatively uniform, and electrostatically controlled surface reduction capabilities suitable for potential applications in areas like hybrid bonding pre-treatment.

Reference

[1] Tadatomo Suga, Ran He, George Vakanas, and Antonio La Manna, "Chapter 6 Direct Cu to Cu Bonding and Other Alternative Bonding Techniques in 3D Packaging", in 3D Microelectronic Packaging 1st ed., Yan Li and Deepak Goyal Ed., Switzerland, Springer, 2017, pp. 129-156.